MITOCW | Chemical and Biological Effects of Radiation, Smelling Nuclear Bullshit

MICHAEL SHORT: So, today we're going to get into the most politically and emotionally fraught topic of this course for stuff on chemical and biological effects of radiation. Now that you know the units of dose, background dose, we're going to talk about what ionizing radiation does in the body, to cells, to other things, and we're going to get into a lot of the feelings associated with it.

And by the end of this lecture, or Thursday, I'm going to teach you guys how to smell bullshit. Because we're going to go through one of millions of internet articles about things that cause cancer, that don't cause cancer. In this case, it's going to be radiation from cell phones.

So I'm going to try to reserve at least 10 minutes at the end of this class for us to go through a bunch of quote, unquote, studies and misinterpretations of those conclusions. And I was going to pick my favorite of the 44 studies, and looking through them all, my favorite are all of them.

AUDIENCE: [LAUGHTER]

MICHAEL SHORT: So we'll see how many we can get through. But let's get into the science first, so you can understand a bit about what goes on with ionizing radiation. Like radiation damage in materials, radiation damage and biological systems is an extremely multi-time-scale process.

Everything from the physical stage, or the ballistic stage, of radiation damage to biological tissues acting on femtoseconds, where this is just the physical knocking about atoms and creation of free radicals, these ionized species, which in metals you wouldn't care about, in biological organisms you do because then they undergo chemical reactions from the initial movement and creation of other strange radiolytic species and the diffusion and reaction of those things, which starts and finishes in about a microsecond, before most of these things are neutralized.

And then, later on, the buildup of those oxidative byproducts of these chemical reactions undergo the biological stages of radiation damage. All of the free radicals with biological molecules have reacted within a millisecond. So radiation goes in, a millisecond later the damage is done.

Then you start to affect, let's say, cell division. It takes, on average, minutes for a rapidly dividing cell to undergo a division. That's when the effects would first be manifest from a DNA mutation. But then it'd take things like weeks, or years for these sorts of things to manifest in a health-related aspect. So, the division of one cancerous cell into two won't change the way your body functions, but the doubling in size of a tumor that blocks other tissue absolutely would.

And so, it all starts in this sub-femtosecond regime, when most of you-- well, for this entire year, we've been approximating humans as water. We're going to continue to do so for the purposes of these biological effects. So, let's say you, a giant sack of water, gets irradiated by a gamma ray. And that gamma ray undergoes Compton scattering. Which, now you know how to tell what the energy of the Compton electron would be.

We never talked about what happens with the molecule where it came from. That molecule remains ionized. And since you're not especially electrically conductive, they're not neutralized immediately. And you can be left over with either a free radical or an electron in an excited state. And then what happens next is the whole basis of radiation damage to biological organisms.

These free radicals can then encounter other ones, and let's say an H_2O^+, can very quickly find a neighboring water molecule, which they're almost touching and form OH and H_3O. This is better known as H^+, and that OH is a kind of unstable molecule. And these excited electrons here can also become these H_2O^+'s, leading to this cascade of what we call radiolysis reactions. There's a few of them listed here, things like an OH plus an aqueous electron, which could come from anywhere, like Compton scattering, like any other biological process that frees an electron, can make another OH^-. So you can locally change the pH inside the cell that you happen to be irradiating.

Or, let's say any of these oxidative byproducts could encounter DNA. Rip off or add an electron to one of the guanine, thymine, or other two or three bases in DNA or RNA, then you've changed the genetic code of the cell. In the progression of these radiologists byproducts, like I mentioned, whether you go by excitation or ionization, then you start to build up these six species-- these five species tend to be-- or these six ones tend to be the ending byproducts of a whole host of radiolysis reactions.

And don't worry, you're never going to have to memorize all the radiolysis reactions because the mechanism map is fairly complicated and there are multiple routes to creating each one. But the ones that are highlighted here in these squares, are the ones that end up building up in your body, things like peroxide. Has anyone ever put peroxide on a wound before? What happens? Yell it out.

AUDIENCE: It bubbles up.

MICHAEL SHORT: Bubbles up. What happens when you form peroxide in your body from radiation?

AUDIENCE: It bubbles up.

MICHAEL SHORT: Well, luckily it doesn't quite bubble up on the macro scale level, but it is a vigorous oxidizer. 90% H2O2 is used as rocket fuel, as the oxidizing species in rocket fuel. You don't make 90% H2O2 from getting irradiated, but every molecule counts. Things like O2, you're shifting the amount of oxygen in the cells. And then there's things like these superoxide radicals, or H2O-, H2O+, or all these other things that are available to rip off or add an electron to something else that normally wouldn't have it.

And the list of these potential reactions, as well as their equilibrium constants and activation energy, is huge. Here's half of it. Notice a lot of these equilibrium constants shift really strongly one way or the other. So, just because these molecules are made, doesn't mean that all of them end up staying and doing damage. But unless these rate constants are either 0 or infinity, there's going to be some dynamic equilibrium of these reactions. So, once in a while, some of these free radicals will escape the cloud of chemical change and charge and get to something else.

Here's the other half of the equation set. And it's under debate just how many of these reactions there actually are. Like, how often would O2- radicals combine with water, which you can see is not quite set in the reaction, to form [? HO2 - NO2 NH+ ?] Kind of a strange little reaction right there. Actually, a lot of them are quite strange. You don't usually think of them happening because these are very transient reactions, whose byproducts do build up. And that's the chemical basis for radiation damage to biological tissues.

Now, once those chemical products form, they have to move or diffuse. So you can actually calculate or get diffusion coefficients for some of these oxidizing species, as well as compute an average radius that they'll remove before undergoing a reaction. So this is part of the basis for why alpha radiation is a lot more damaging than gamma radiation.

Chances are, if you incorporate an alpha emitter into the cell, it does a whole bunch of damage. That damage consists of these oxidative chemical species, that, if they're that far away from neighboring atoms that happen to be in DNA, they might do some damage. Whereas, isolated Compton scatters and photoelectric exhortations from gamma radiation, not so much. Chances are you hit random water in the cell that isn't quite close to anything, fragile, and not much happens.

But you can also see this by looking at charged particle tracks. These things can actually be experimentally measured. By firing electrons into gel or film or something like that, you can actually see tracks of ionization and watch them as a function of time. In this case, it's a simulation of a charged particle track at different timescales.

So, right here, this 10 to the minus 12 for the time in seconds, tells you where these radiolysis products are. And the N number, here, tells you how many of those remain. So after a picosecond, you can pretty much just trace out the path that the electron took, starts off right here. What do you guys notice about the density of the charged particle track as it moves from the source to the end?

AUDIENCE: It's much more dense at the end.

MICHAEL SHORT: It's much more dense at the end. And why do you think that is?

AUDIENCE: Stopping power.

MICHAEL SHORT: OK. More than just-- yeah. Stopping power, yes, but fill in the beginning and end of that sentence. Chris, do you have your hand up?

AUDIENCE: [? It's all good. ?] So, it's a charged particle, so it drops off most of it's energy where it has the least amount of energy, so it does the most damage [INAUDIBLE].

MICHAEL SHORT: That's right. So, you're actually visualizing the change in stopping power as a function of charged particle energy. It comes in, has a very high energy. And it might knock a little radiation damage cascade by hitting another electron, which can have its own shower of ionization. And then it moves while doing nothing, in this straight line, until it hits another one.

And notice right at the end, that's where the densest amount of damage is done because that's where the stopping power is the highest. It's also where the energy is the lowest. So, this is where the worlds of and physics collide. You can actually visualize stopping power, like actually visually in gel or on film or on a computer by watching these charged particle tracks.

And after 10 to the minus 12 seconds, all the ballistics are over. Then you end up with diffusion and reaction. So, it's going to be a balance between these charged particles moving away from each other and finding something else, or finding each other and re-combining. And that's why, as you go up in timescale, the particle tracks get more and more diffuse and the number of these remaining free radicals goes down until you level out at about a microsecond, when all of the different particles are so spread out that there are none touching each other anymore.

To refresh your memory a bit from a few seconds ago, take a look at some of the charge states of these oxidative byproducts. Some of them plus, some of them minus, sum of them excited, all over the place. So they can react with each other, which is something you'd want to encourage so that they don't go and find something else, causing biological damage.

There's a question on last year's OCW problem set, that I'm not giving you for this one, which is, calculate the radiation resistance you would get by getting cryogenically frozen. So here's a question that I don't think a lot of cryogenicists ask themselves, if you want to preserve a human for 10,000 years and wake them up later, how much radiation damage are you going to get? Ever think there's a cryogenicist that ask themselves that question? I don't actually know. But it's not a question I've ever heard before, which is why I made it a problem set question. Because I know the answer is not out there. I looked for a while.

Let's switch particles for a second and look at the charged particle tracks from a proton. What differences do you see between the proton and the electron charged particle track? So, proton, electron. Proton, electron.

AUDIENCE: There's no curve.

MICHAEL SHORT: There's what?

AUDIENCE: There's curve. It's straight.

MICHAEL SHORT: Its straight. Why do you think it's straight? Why does anyone think it's straight?

AUDIENCE: They're bigger.

MICHAEL SHORT: They are bigger, more massive. So the same deflection, the same transfer of momentum, to an electron using our beloved hollow cylinder approximation thing, causes less of a change in direction for a proton as it does an electron. The forces are the same. They're both just a plus or minus 1 hitting a plus or minus 1 charge. But the mass is quite different on the proton, so it doesn't get deflected as much, which is why the charged particle tracks are so straight.

Now, what are these things here? What are those offshoots?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: They're secondary charged particle tracks. So, let's say a proton hits an electron, that electron can have any amount of energy, probably going to be lower than the proton did. And it's going to cause its own little damage cascade right there.

And, just like before, you can track the number of these charged particle trucks moving from 5000 to about 1000, between, let's say, 10 picoseconds and a little less than a microsecond. And once these charged particles have spread out or diffused away, chances are recombination has gone down quite a bit and they're going to go react with other things.

And this is a perfect analogy to radiation damage in metal. So, radiation damage in biology is like radiation damage in material science. You have this initial cluster of damage, in materials it's usually vacancies or intestinals, in biology it's charged particles. But when they're in a dense cascade they can recombine with each other. And the ones that miss each other go off to find either other defects in the material or other atoms in your cells. It's a very fitting analogy. Yeah?

AUDIENCE: How come we don't see like a denser [INAUDIBLE] to the proton [INAUDIBLE] electrons?

MICHAEL SHORT: Let's see. I don't know if we see the whole charged particle track here. You're right, it doesn't look like the density changes very much. You can't even really tell where the source is. We may not be looking at the whole thing.

Here's another question. So, it's a 2 MeV proton. That scale bar is 0.1 microns. Let's do a quick simulation to verify this idea. Luckily we have the tools to do this, soon as I clone my screen. Let's use SRIM and find out what is the range of 2 MeV protons in water. And if it's more than about a micron, which is what's shown-- well, let's say, that's 2 microns. If it's more than 2 microns, what's shown on the screen, it means we're not seeing the whole track. SRIM.

Good, you can see it.

So let's say, hydrogen at 2 MeV, going into something consisting of H and O in a ratio of 2:1, make sure its density is correct for room temperature water, and let's look at a range of 25 microns, because I kind of already know the answer.

AUDIENCE: [LAUGHTER]

MICHAEL SHORT: Much more than 25 microns. So, our initial assertion was correct. Let's actually find out what the range is. Let's put 40 microns. Whew, it's a little more than I thought. Protons in water, at just 2 MeV. Let's fly tons of them. Wait til we get about 1,000. Look at the range. Make it bigger so you can read it. 75 microns. 75.5 micron range. There you go.

Let's go back to the big one. So, there you go. If this scale bar is 0.1 microns, you're looking about 2 of the 75 microns of charged particle track. Interesting, no one picked up that question last year, but I'm glad you did. I'm glad we were able to show you where it comes from. So this will look quite different if you're looking at the end of the charged particle track. Cool. Good question.

To look really, really close up, you see a lot more of this branching again. So whenever a proton strikes, let's say another atom or an electron, you get your own little dense damage cascade. And look at that, not much until the very end when you get this cloud of damage popping off at the end. So, yet more examples of the physics that you've learned popping up in biological systems. The difference is it's water not metal, but otherwise everything's the same.

And then we get to what's called G-values. I don't know why it's called G, but I'll tell you what they mean. It's the number of each species, per 100 MeV, found later, at let's say, 0.28 microseconds, or typically 1 microsecond, for different particles of various energies. These are relative effectiveness' of these particles at different energies to leave oxidative byproducts by.

So there's a few things that are wrapped up into these G-values. So, notice that, in this case, here's a G-value for electron energy. At different energies, you'll have different amounts of OH, H3O in such, per 100 eV of energy. So the unit of G-values here, it's like number of chemical species per 100 eV of energy. So it's an energy normalized measure of the effectiveness of radiation making chemicals. Does make sense to folks? If not, raise your hand and I'll try to re-explain. OK.

AUDIENCE: Please repeat it.

MICHAEL SHORT: Yep. So a G-value, it's got units in concentration per unit energy. And it's a measure of how many chemicals a given particle will make as a function of its energy. And these particles are the ones that survive the recombination and end up diffusing to other species. So, these G-values, it's kind of like how many oxidative species are made that go off and damage other things?

Let's look at some trends right here. For things like OH, for electrons, what sort of patterns do you notice in the data? And take a sec to parse some of these numbers. Just look at the top three rows. What pattern do you see?

AUDIENCE: Starts high and then goes--

MICHAEL SHORT: Starts high, goes low, goes high again. Why do you think that is? Straight from the physics. At super low energies, 100 eV electron, you'll make, on average, 1 OH radical for every 100 eV of energy. As you increase in energy, you start making fewer and fewer per unit-- actually, that's not the one I want to look at. That's a different species. Let's see. No, that is. OK. That follows the pattern that we're looking for.

AUDIENCE: Does the high energy includes stuff that's created from causing secondary cascades?

MICHAEL SHORT: Oh, yeah. This is just total number from everything. Right? It's just the number of each chemical species left over after a microsecond. So what do you think could cause this initial increase and then decrease and then increase?

AUDIENCE: Is it because of the cross-sections of different particles?

MICHAEL SHORT: Part of it. The cross-sections that also go into the stopping power. That's part of the answer. So at really low energies, you're already at your stopping power peak. And that way, for the little bit of energy you have, chances are it's going to ionize different things. Then as you increase your energy, you have more and more of that range of the particle in the lower stopping power region.

So, you'll have more of the-- let's see. You'll have more and more of that particle-- let me try and phrase this quite well. Let's go back to the charged particle tracks for electrons, and I'll get this-- yeah, here we go. So, when you're electron comes in a really, really low energy, you're in that region right there. Chances are you're going to make a lot of those oxidative byproducts.

And then as you go a little higher in energy, you make fewer per unit distance-- or you make fewer per unit energy. You can think of that as the spread, right there. But then also, as you go way higher in energy, your ability to ionize increases. So you've got that sort of 1 over E term in stopping power making things worse. And you've got that log of E term in stopping power making things better. And if we go back to the data right here, for those top three or four, it tends to follow that trend pretty well.

Now what about things like H202? What sort of trend do you see there?

AUDIENCE: The opposite.

MICHAEL SHORT: The opposite. So, I'll give you a hint. H2O2 isn't directly made by radiolysis, it tends to occur by reaction of other radiolysis products. So it's like a secondary chemical, not a primary produced chemical. So, why do you think H2O2 follows the opposite trend?

AUDIENCE: It comes from the-- not the decay, but like a reaction from one of the previous ones, that there's more of that first species there, that it hasn't reacted to form it yet. But once it is lowered, that means it's made more of the H2O2.

MICHAEL SHORT: Sure.

AUDIENCE: And then vice versa.

MICHAEL SHORT: Yeah. So, to rephrase what Sarah said, in this energy range right here, you're producing this fairly dense cascade of oxidative byproducts. When those reactions occur, they tend to make things like H2O2, something that's not made directly from radiolysis, but indirectly from recombination of those chemicals.

And then as you raise the energy more and more, to like 20 keV, you start making those primary products more spread out. They're not as close to each other. They don't recombine as much. They don't make as much H2O2. They'll tend, instead, to spread out a little more. So more will survive. More of these primary ones will survive, and not react to make as many of the secondary ones.

So, how is that explanation fitting with you guys? Cool. So, it's a balance between intermediate energies. You make a whole lot of primary ones, which are so close that they react to make the secondary species much more easily. As you raise the energy of the particles going in, you make more isolated primaries that can't find each other, and they don't make as many secondaries per unit energy. Yeah?

AUDIENCE: How come for like the 100 eV H2O2 it's less? Because since it's making a lot of the initial, or the primary, byproducts, wouldn't you expect it to also make a lot of the secondary because they're also close together?

MICHAEL SHORT: You might, except at very low energies, our idea of stopping power isn't quite as complete. So, by what other processes can electrons lose energy at really low energies? You could have a deflection without an ionization, right? Just a simple-- let's say, you could have an excitation, you could have just coulomb deflection, you can have neutralization. You can have all those really, really low energy things that go on, that don't end up producing as many ionizations. Because you need to produce an ionization or an excitation to kick off radiolysis.

So then, when you get high enough in energy, and chances are you'll ionize rather than undergo one of these really low energy inner loss mechanisms, then you start making more of the primaries, but densely, which make more of the secondaries. Then as you go even higher in energy, you still make tons of primaries, but since they're spread out more, since the stopping power is lower, they don't find each other and they don't make as many secondaries.

So, let's look at some other numbers and trends, different particles. First of all, for protons and for alpha particles, note here that the scales are in MeV. Whereas, the G-Value is for electrons in the keV range, and for protons in the MeV range are pretty much the same, on the same order of magnitude. Anyone have any idea why?

AUDIENCE: They're heavier.

MICHAEL SHORT: They're heavier. And then what does that lead to in terms of a stopping power?

AUDIENCE: They're easier to stop.

MICHAEL SHORT: They're actually harder to stop. If they're heavier, than the deflection of an electron doesn't stop them as much. And so that way, more of these proton and alpha radiolysis products are going to be more spread out. So you get the same number per 100 MeV, in the MeV range, as you do for electrons at a much lower energy.

But then alphas also have this interesting thing that they're doubly charged, so that those coulomb forces, remember it's by Z squared, so it's four times as strong. So, let's see, how do they compare? Yeah. There aren't really enough data to draw those nice trends that you could see from electrons.

But we do have some other interesting trends in the G-values as a function of temperature. So these right here are G-values for H and OH by gamma rays, which are two primary species. And here we've graphed them as a function of temperature. Why do you think the G-values, or the amount of radiolysis products that survive a microsecond, increase with temperature? What's this a competing force or a balance between? So once these products are made, what are the two things that they can do? Anyone?

AUDIENCE: Recombine or diffuse.

MICHAEL SHORT: Recombine or diffuse. Good. Which of these will increase much more strongly with temperature?

AUDIENCE: Diffusion.

MICHAEL SHORT: Diffusion. If they spread out more at higher temperature, then they'll separate from each other and not recombine as much. So a whole bunch will be made, no matter what, in a matter of femtoseconds. But at a higher temperature, more of them diffuse away from each other and survive the cascade, rather than recombining. And so that's why, when you look at any primary species, H2 or H or anything like that, you're going to see an increase in G-values with temperature.

What do you guys think is going to happen to these secondary byproducts with temperature?

AUDIENCE: Decrease with temperature.

MICHAEL SHORT: Decrease. And why do you say so?

AUDIENCE: Well, if they're made from the primary products and the primary products are surviving more because they're separating, then the secondary ones are just going to be less.

MICHAEL SHORT: Yeah. If the primary ones are surviving more, you're not going to make as many secondary ones. And that's just what we see. Number of free electrons left, or especially things like the amount of H2O2, it's all going to be in balance. And if more primaries survive, you don't make as many secondaries as a function of temperature.

One, these heavy ones are slower to diffuse. But two, they're not made as much because the primaries escape each others pull and go off to damage something else. In a reactor, this would be metals causing oxidation. In a body this would be you.

And so let's get into the materials aspect of this to give you a more-- a less biologically damaging view of what can radiolysis really do. It's quite relevant to all reactors, including the Fukushima reactor. The idea there is that the reactor was flooded with seawater, which introduces chlorine, which greatly changes the balance of radiolytic byproducts. And this can actually be directly studied. There's an experiment just a few years ago-- two years ago, where they wanted to figure out what is the influence of radiolysis on corrosion? If you're making all of these Hs and OH-s and H2O+s, does it change the corrosion rate of materials in the reactor?

So they built a high-pressure cell, that they fill with high-pressure, high-temperature water. And they've got this little disk of metal with a thin membrane right there. It's thin enough that protons can pass through it and cause radiolysis to occur right in this little pocket where the water is. And so where the protons are, you get radiolysis. Where the protons aren't, you get regular old water corrosion.

And the results are pretty astounding. You can see the irradiated zone in extra oxide thickness. So you can see where the protons were because radiolysis sped up the corrosion rate as a single effect. Right nearby, not 100 microns away, was the same water, at the same temperature and pressure, just no protons and no radiolysis.

To look at a cross-section, you can very clearly see the difference in oxide thickness way out in the unirradiated zone or in the irradiated zone. And you can tell right here how many protons there were, until right over here where there were none. So it's a very striking example of, well, this is what radiolysis does in reactors.

And we actually do things in reactors to suppress radiolysis. We inject hydrogen gas. So there's a hydrogen gas overpressure injected. One of the main reasons is to suppress radiolysis. Because if I jump back to any of these reactions, a lot of them involve H2. And if you dump a whole bunch of H2 into the reactor, you push the reaction backwards in the other direction.

From straight up chemistry, if you add a reactant and add a product, you push the equilibrium in the other direction. That's why we do this in terms of injecting hydrogen into light water reactors. And if you look at the amount of hydrogen injected in a PWR, a pressurized water reactor, which comprises 2/3 of the reactors in the country, it's like 20 to 30 cubic centimeters per kilogram of dissolved hydrogen. That's quite a bit. And the whole idea there is to suppress radiolysis and suppress corrosion. So I find it to be pretty cool. So a knowledge of G-values can keep your reactor from corroding.

Then let's get into the biological effects. In the end, for the long-term effect it's all about what happens to DNA. Because if a cell mutates, it can either kill the cell so that it can't replicate, or you can cause a mutation that might make some sort of a change and change the cell's function. And so you may imagine, a lot of this stuff is done in LET, linear energy transfer. Again, another word for stopping power.

If you look at the density of these damaged cascades as a function of stopping power, LET. You can see that for high-energy electrons, or beta particles, they just bounce around with a lot of distance between interactions, causing very relatively little damage on the way. For Auger electrons, again electrons, but at a much lower energy. They're at the end of their stopping power curve and they cause a lot more damage wherever they're emitted because already, they're going to make a much denser damage cascade.

Alpha particles just go slamming through. It's like rolling a tank through your cell pretty much. Because there's going to be a ton of interactions from charged particle interactions, you won't really change the path of that alpha because an electron imparts very little momentum to an alpha particle. And if DNA happens to be in the way, it's going to get damaged. This is a lot of the reason why there is relative effectiveness of different types of radiation.

We talked last week about these quality factors, gamma rays are 1 electrons tend to be pretty close to 1 alphas tend to be 20. Because the same energy alpha particle will impart a ton more damage locally than the same energy beta particle. So can you guys see visually where these quality factors come from? Cool.

And there's two types of DNA damage, direct and indirect. Direct damage is what you might think radiation comes in and ionizes something in the DNA, either causing, let's say, 2 thymine-based bridge, like a kink in the DNA, or destroying it or doing anything. But most of the damage is done indirectly because the amount of volume of DNA in your cells is extremely low. Has anyone ever done the old high school bio experiment, where you extract DNA from onions?

AUDIENCE: Yes.

AUDIENCE: Strawberries.

MICHAEL SHORT: Strawberries. Anything? So how did you do it? Anyone remember how this was done?

AUDIENCE: Some chemicals and stuff.

AUDIENCE: You have to mix in good solution with a bunch of good stuff and [INAUDIBLE]

MICHAEL SHORT: So you take, let's say, an onion, mix it in solution with a bunch of stuff, and you end up with this gigantic booger, which happens to be DNA. It's like a three-foot snot thing. But what was the volume of the DNA compared to the volume of the onion?

AUDIENCE: Quite small.

MICHAEL SHORT: Quite small. There's not a lot of DNA in cells. So the direct damage route, while still there, comprises very little of the damage done to tissue. Mostly it's indirect because surrounding all DNA is the rest of your cellular fluid, which consists mostly of water. And as we've seen all today, water undergoes radiolysis. Those radiolytic byproducts can diffuse, find their way to DNA, and cause the same sort of ionization that direct radiation would do. And since that volume is much larger, let's say the hollow cylinder of water surrounding your DNA, this is the most likely route to cellular damage. And--

Actually I want to skip ahead to something real quick, you can actually use that to your advantage because it can kill tumor cells. So tumors are rapidly dividing masses of cancer cells. If those cells are rapidly dividing, then DNA is being replicated much more readily. So you can inject something that will bind to DNA, like this little chemical right here, this Iodine-125, whatever, whatever, which mimics thymidine, something that would be found in your DNA, but absorbs radiation much better.

So you can inject this iodine-containing organic molecule, which binds somehow to DNA. I'm not going to even guess how it works. But, if you want this to get damaged, then you want-- let's say, your DNA to get preferably damaged, the tumors are replicating faster, they're going to incur more damage from the same amount of radiation. So the same process that causes cancer can be used to cure cancer, interestingly enough.

And so, good, we do have about 10 or 12 minutes to talk pseudoscience. So now that you know a little bit about how radiation can cause cancer and mutations and you know a lot of the physics behind how much energy do you need to cause an ionization, let's start knocking off these questions one by one. So, this field, more than any, is fraught with garbage, absolute garbage science. I won't even say pseudoscience because that almost makes it sound half legit. Garbage, misinterpretations, lies, poorly done studies, misinterpretations of abstracts and conclusions.

And today I'd like to focus on cell phones and do they cause cancer? Very hot topic. There's lots of people with predetermined agendas that want to say all electromagnetic radiation is bad and we should go back to an agrarian society where nothing happened. Well, I'll give you a hint, Cambodia tried that and it didn't turn out too well. People have interesting notions of what's real and what's not.

So let's start looking at some of these. There's an article written by this fellow, Lloyd Burrell, around November, 2014. It looks like it was republished somewhere in 2016. Let's just start looking at the facts. So, what I want to start doing here is cultivating your nose to be able to smell bullshit because this is a lot of what you're going to be doing, in terms of public outreach.

As nuclear scientists you will be called on to provide expert advice and say whether things are real or not, explain why, and do it in an empathetic way so as not to make people feel stupid. Because it's very easy for someone to read this and think, yeah, I should be afraid. Cell phones cause cancer. It's a natural reaction to feel.

Let's take a look at some of these facts. Cell phones emit microwave radio-frequency radiation. True or false?

AUDIENCE: True.

MICHAEL SHORT: True. Yeah. These are microwave emitters, or RF emitters. What sort of energy is microwave radiation emitted at? Just give me an order of magnitude, MeV, eV, keV.

AUDIENCE: MeV?

MICHAEL SHORT: Little MeV. Fractions of an eV. It's far beyond the visible range in the lower energy spectrum. Can a milli-electron-volt photon cause an ionization directly?

AUDIENCE: No.

MICHAEL SHORT: No. Microwaves and RF non-ionizing radiation. They can cook things by heating up water, but they do not cause ionizations the way that ionizing radiation does. This radiation has an ability to penetrate our bodies. True or false?

AUDIENCE: Yeah, [INAUDIBLE]

True.

MICHAEL SHORT: True. It gets through us, right? Radio waves are going through us all the time. Our governments do virtually nothing to protect us from these dangerous.

AUDIENCE: Technically, but what dangers?

MICHAEL SHORT: Technically, true. Yeah. So this is a classic example of fear mongering, taking a bunch of facts, putting them together to elicit an emotional response that is incorrect. And because the emotional part of the brain kicks in far faster than logical part of the brain, that's how we're wired, it elicits a reaction with a predetermined conclusion. And yet, there is strong evidence, multiple peer reviewed studies-- I'm not even going to read the rest of the sentence because I don't want to go on record saying it as if it were true.

Let's, instead, look at the studies, because that is the stuff that we should trust.

AUDIENCE: [INAUDIBLE] 44 studies.

MICHAEL SHORT: 44 studies cited. And let's look at some of the reasons. Let's see, there's a little bit-- I have to make it a little smaller. Can you guys still read that at the back? Or actually, no, make it a little bigger and forget the sidebar. That's better. OK.

I was going to pick a couple of these to show you and I started going through them and my favorite ones are all of them. Most of the studies are perfectly legitimate, some of them are not. Most of the interpretations by this Lloyd fellow are absolutely wrong, and either done ignorantly, which somewhat forgivable, it can be hard to parse these studies, or intentionally. We don't know which one. Let's look here.

"Telecoms giant," et cetera, "commissioned an independent study--" 404, not found. Let's go to the next one. We can't conclude anything from that.

The Interphone Study found that: "regular cell phone use significantly increased the risk of gliomas," some type of tumor, "by 40% with 1,640 hours or more of use." Let's look at the key figure, taken from this paper, and blow it up so you can see it. What do you guys notice about this figure?

AUDIENCE: [INAUDIBLE]

AUDIENCE: It's so [INAUDIBLE].

MICHAEL SHORT: Forget the low resolution. We can't knock that because it might be a copy. No error bars. And what does most of this cell phone use-- and the unit not shown here is, I think it's like hours of use?

AUDIENCE: It's all about the same.

It's basically all the same.

MICHAEL SHORT: Yeah.

AUDIENCE: [INAUDIBLE] by any chance [INAUDIBLE]

AUDIENCE: The never is actually closest to the 1.

MICHAEL SHORT: Except for this one. Blue line is odds ratio. A lot of these things are given in OR, or odds ratio. Let's say the fractional-- or let's say the multiplying factor for increased risk of finding cancer in the variable group compared to the control group. And control and variable are interesting topics I want to make sure people have. So we have the Interphone Study cited in many of these papers.

Let's see. OK. Garbage, garbage, opinions, opinions. Let's go find the study. This is something I wish people did more, is go to the study itself. Yeah, the Interphone Study.

AUDIENCE: Overall, no increase in risk.

[LAUGHTER]

MICHAEL SHORT: We'll make this bigger to make it more obvious. So many people-- this article's been cited almost 500 times. I don't know in what capacity because I haven't looked up every citation. But a lot of what this site and other sites do is cite the Interphone Study to say cell phones cause cancer. Read the conclusion.

AUDIENCE: Rise of an era. Prevent [INAUDIBLE] interpretation.

MICHAEL SHORT: Yes. So this study is not a bogus study. The study was done correctly, reporting ORs, these odds ratios, with 95% confidence intervals. If you just look at the numbers itself, oh man, 1.15 odds ratio, 15% higher incidence of cancer, with a confidence interval that includes less and more. So you cannot conclude with 95% confidence that this data is correct. And the authors very honestly say, no conclusion can be drawn, require further investigation.

What does this Lloyd fellow say?

AUDIENCE: Cancer.

MICHAEL SHORT: Cancer. Yeah. An either accidental or deliberate misinterpretation of the data. OK, let's go to numbers 2 and 3. I don't need those anymore. Let's see, number 2. Oh, we did number 2.

Number 3, again from the Interphone Study. We can discount that because we've now read the conclusion of the study and looked at a bit of the difference.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Number 4, "Harmful Association Between Cell Phone Risk and Tumors."

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Let's see.

AUDIENCE: It says there's possible

AUDIENCE: Possible. Studies providing a higher level of evidence are needed [INAUDIBLE].

MICHAEL SHORT: Again, honest authors. I applaud the authors for taking a controversial topic, doing a fair bit of data, with at least enough metadata analysis, I think the sample size is OK, and then saying, higher level of evidence is needed. What does the internet say? It takes the one sentence that they want to support their predetermined conclusion. Very dishonest, if you ask me.

Number 5. Oh, this is fun. OK. What does number 5 say?

AUDIENCE: Does this not just make you angry?

MICHAEL SHORT: Huh?

AUDIENCE: Does this not just make you angry?

MICHAEL SHORT: Yes it does make me angry. This is why I'm showing it to you. - infuriating, right? But some of the comparisons between what the folks on the internet will say with the sentence that they want to say- and then you go to the actual study, which they do give you the link for, "a consistent pattern of increased risk associated with wireless phones." What does the study say? Take a sec to parse this. I'll make it a little bigger. When you see an odds ratio of, let's say, greater than 1. And see a confidence interval--

AUDIENCE: Oh, holy crap.

AUDIENCE: Oh! [INAUDIBLE]

MICHAEL SHORT: Yeah. Again, another odds ratio and another confidence interval. Another odds ratio, another confidence interval.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Interesting. The one interesting part is for what they call ipsilateral cumulative use, which means a tumor found on the same side of the head as the cell phone, there is actually a confidence interval that seems to be significant. So, I'm not going to trash this study. I'm going to say it's not quite conclusive. It doesn't go out and say cell phones cause cancer, despite this fellow coming out and saying cell phones cause cancer.

OK, moving on to number 6, was a 404. Let's just confirm. Wasn't able to get it an hour ago. Oh, it's back. OK, let's see what it does. I don't even know what this one's going to do.

AUDIENCE: [INAUDIBLE]

AUDIENCE: Potential [INAUDIBLE]

AUDIENCE: Possible association with [INAUDIBLE]

AUDIENCE: What's heavy mobile phone use?

MICHAEL SHORT: Heavy mobile phone use, yeah. Well, they'll define that somewhere in the article. So, some of these studies, it's like OK, there's interesting viewpoints to be seen. They shouldn't be ignored just because we have this predetermined conclusion that cell phones don't cause cancer. It's important to go and actually look at the studies and decide for yourself.

Let's get into the fun ones. Number 7. "A recent study on 790,000 middle aged women found that, "women who used cell phones for ten or more years were two-and-a-half times more likely," et cetera, et cetera. "Their risk increased with the number of years they used cell phones."

Let's look at the study. OK, That's. Not the study, so we need to go find the study. And that's another news article about the study, we need to go find this study. Ah, finally.

AUDIENCE: The study.

MICHAEL SHORT: The study.

AUDIENCE: The study.

MICHAEL SHORT: Read the conclusion.

AUDIENCE: What the-- I'm so bad. [LAUGHTER]

AUDIENCE: I don't think the people writing these articles are actually like reading these--

MICHAEL SHORT: No, I don't think so either.

AUDIENCE: They just look at the title and they're like, [INAUDIBLE]

MICHAEL SHORT: So, the best thing that you can conclude about these sorts of people is that they're not reading the studies and reporting on them. If they are reading them and not getting it right, no, not everyone can parse the science. If they're reading them, understanding them, and cherry picking the facts in order to support their conclusion, that to me should be criminal.

We do live in a country where there's freedom of speech. You're free to say whatever you want, as long as it's not hate speech of various kinds. It doesn't have to be right. You also don't have to listen. So just because you have freedom to talk, doesn't mean people have an obligation to listen. And this is the problem with a lot of this.

So I think my-- yeah, my notes for this study was just kind of the F word. It was, how do you get the conclusion from this internet article, which wrote an article about an article about an article about a study, when the conclusion says, with an excellent sample size not associated.

OK. We have like five or seven minutes left, so let's skip ahead. I had a fun one for number 12, cancer of the pituitary gland. Let me get rid of the other stuff.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Oh, does that look like a surprisingly familiar figure?

AUDIENCE: Cool.

MICHAEL SHORT: It's another article about the same study. Let's just confirm.

AUDIENCE: [INAUDIBLE] articles about--

MICHAEL SHORT: Oh, look at that.

AUDIENCE: [INAUDIBLE] papers.

MICHAEL SHORT: That right there was the article written about the study, where the other link was an article, written about the article, written about the study. OK. What else? Next one. Let's just keep going in number order. Israeli study about thyroid cancer.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: OK.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: This appears to be a blog, so let's search for the word "Israel."

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: OK, but first the news article. So take a sec to parse some of this. "The incidence of thyroid cancer has been increasing rapidly in many countries, including the US, Canada, and Israel."

I mean, one thing to say-- let's say, case control research on this topic is warranted. Sure. No one's going to refute a claim that, hey, maybe we should study something properly, right? Let's go a little further down. Let's try to find the actual study. Where is this study? Interesting. The main point of the study is that thyroid cancer and cell phone usage are going up at the same time.

AUDIENCE: Wow!

MICHAEL SHORT: This is the point where I like to say correlation does not imply causation, and hammer that point home by going to one of my favorite blogs, *Spurious Correlations.* You can find any data set that correlates with any other data set.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Let's look at some examples. US spending on science, space, and technology correlates with a 99.79% correlation of suicides by hanging, strangulation, and suffocation.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Correlated, yes. Causal, I don't think so.

[INTERPOSING VOICES]

MICHAEL SHORT: Yeah. Divorce rate in Maine correlates with per capita consumption of margarine.

AUDIENCE: [LAUGHTER] Michelle, [INAUDIBLE] margarine.

MICHAEL SHORT: You can find a link between anything and anything else if you just search the data long enough without searching for a mechanism or a reason.

AUDIENCE: That's cool.

Can we look at the age of Miss America below this?

MICHAEL SHORT: Oh, OK. Age of Miss America correlates with murders by steam, hot vapors. [LAUGHTER]

AUDIENCE: [LAUGHTER]

MICHAEL SHORT: Clearly, we should ban the Miss America pageant or make them older.

AUDIENCE: Yeah, [INAUDIBLE].

MICHAEL SHORT: Or the other way around, make them younger. Maybe this is why we have toddlers in tiaras, it's to stop murders by steam. Oh, my God. OK.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: So this is, again, the point where you have to ask yourself, what are the other confounding variables in this study? Why else could thyroid cancer be going up? Anyone? I can probably come up with like a hundred different possible reasons.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Any sort of other chemicals? Let's say, more industrial runoff, more urbanization, smog, inhalation, some amount, let's say, I don't know, iodine released from Chernobyl making its way through. Now, that would have had like a 30-day half-life.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Yeah, that's also got to pretty much decay by now. Yeah, there could be any number of reasons. And just to say cell phones and thyroid cancer are correlated, is like saying this. What else?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: This I think might actually have something to--

AUDIENCE: [LAUGHTER]

MICHAEL SHORT: There might be a link here. Revenue generated by arcades kids with computer science doctorates. Again, just a correlation.

AUDIENCE: [INAUDIBLE]

AUDIENCE: Sociology doctorates-- [LAUGHTER]

MICHAEL SHORT: Ah, look at the amazing-- it's got all the same humps. And everything. All right, I think I've made the point.

AUDIENCE: Actually, I like the margarine and the divorce rate one

MICHAEL SHORT: Let's go on to some of the other studies, let's say, number 15. 11 of 29 cases of neuroepithelial tumors, cell phone users accounted for 11 of them." 11 of the 29 people in the study that got this type of tumor used cell phones. What's wrong here?

AUDIENCE: Who doesn't use cell phones?

People use cell phones.

Everybody uses cell phones.

They don't think about anything else that could have happened?

MICHAEL SHORT: No, no. Here, I think the study is flawed. What is the worst part about this study?

AUDIENCE: [INAUDIBLE]

AUDIENCE: It's only 29 cases.

AUDIENCE: It's 29 cases.

MICHAEL SHORT: 29 cases, sample size. If you get 11 out of 29 and say half of the tumors we saw were attributed to cell phones, that is not a proper conclusion.

AUDIENCE: How are you going to [INAUDIBLE] it to a cell phone [INAUDIBLE]?

MICHAEL SHORT: Let's see, number 17. Ah, OK. Another Israeli study that talked about parotid gland cancers and salivary gland cancers. My note to this is read the last sentence.

AUDIENCE: [LAUGHTER] [INAUDIBLE]

AUDIENCE: Like, I'm sure there's other factors [INAUDIBLE]

[INTERPOSING VOICES]

AUDIENCE: They cause cancer.

MICHAEL SHORT: The blog says, cause cancer. The data says, no causal association. So again, almost criminally ignorant. How many times did you have to miss the last sentence, the conclusion of the article, to pick the part that you want?

AUDIENCE: But everything you read on the internet is true. You know, it's [? illegal. ?]

MICHAEL SHORT: All I can say is everything that you read on the internet was written. That's the best I can say. Number 20, we don't even have to go to the study here.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Oh, boy.

AUDIENCE: [INAUDIBLE] machine learning [INAUDIBLE].

MICHAEL SHORT: Let's check the study to make sure that the quote is actually correct, but before--

AUDIENCE: [INAUDIBLE] Oh, my God.

MICHAEL SHORT: Four women.

AUDIENCE: It's just the one.

AUDIENCE: Study four women. Looks like it might [INAUDIBLE]

MICHAEL SHORT: Yeah, by the prestigious publication, *Hindawi,* which sends me more emails than I read their articles. So let's look at the abstract. Of all four cases, they are a case studies, so striking similarity, how hard do you think it would be to find four women with a certain type of breast tumor? There's a lot of women in the world, right?

AUDIENCE: Yes.

MICHAEL SHORT: And breast cancer is one of the leading causes of cancer in women. It wouldn't be hard to cherry pick four people to get the same conclusion you want. Oh, and there's another correlation, out of 108 billion humans that have ever lived and have been exposed to ionizing radiation, all of them died at some point.

AUDIENCE: [LAUGHTER] At some point.

MICHAEL SHORT: At some point, yeah. every human that's ever lived has died. And every human that's ever lived had been exposed to ionizing radiation.

AUDIENCE: [INAUDIBLE]

AUDIENCE: It must be true.

[INAUDIBLE]

MICHAEL SHORT: Perfect correlation, no causation. Let's see, two more. I think we have time for two more. This is kind of fun. An eye cancer study. All right, let's just go-- "found elevated risk for exposure to radio frequency transmitting devices."

AUDIENCE: Are these real studies? Don't the authors get mad that people are using their studies wrong?

MICHAEL SHORT: I'm sure the authors do get mad, but what are you going to do about some person on the internet, right? You can send a nasty letter to the magazine, which might reject it as hate mail. OK, on the blog.

AUDIENCE: [INAUDIBLE] very strong--

MICHAEL SHORT: What does it say? Elevated risk for exposure in the study.

AUDIENCE: People only get excited by some crazy person.

AUDIENCE: [INAUDIBLE] it's about. [INAUDIBLE]

MICHAEL SHORT: I don't think I have to make my point anymore. We've gone through about half of them. I encourage the rest of you guys to go through the other half. And to the people, like this Lloyd Burrell, I say check your facts. What you're doing is criminally incompetent. With the way that people are misleading the public to get whatever pre-gone conclusions that they have from their emotions or their funding sources or whatever the reason to be, by misquoting facts you're absolutely misleading people and spreading false science. Because, to me, the most exciting moments in science don't end with the words, "I told you so," but start with the words, "that's interesting." So just because the studies that you find don't support your predetermined conclusions, doesn't mean you should reject them. It means that you might have to change your idea.

So, on that note, I'd like to stop here. We'll come back on Thursday and go over the short and long-term biological effects of radiation and look at some more garbage science. Yeah?

AUDIENCE: How do you feel about those wireless chargers they have now? It's like a conductive charger so it uses like a low-branch, strongish magnetic field.

MICHAEL SHORT: Mm-hmm.

AUDIENCE: And people are like, oh, my God. That's so scary.

MICHAEL SHORT: I would just say go to the studies. It's very easy to say put a bunch of rats on a cell phone charger, turn it on, and see what happens. I mean, the data doesn't lie. The reason might be a little hard to figure out. Yeah. Yeah.

So, I mean, another thing is, when people have a predetermined-- I know it's a little past 10:00, but no one's gotten up so I'll keep ranting. So a lot of this neo-environmentalism going on has the predetermined conclusion that only sources of power light on the Earth, like solar and wind, that are renewable and such, are the ways to go. And immediately dismiss nuclear as not part of the environmental solution, despite being part of the environmental solution. A large source of power that's very efficient and doesn't admit any CO2. It might surprise them to know that manufacturing wind turbines is a major source of radioactivity.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Anyone want to guess where?

AUDIENCE: Rare-earth magnets.

MICHAEL SHORT: Yes, thank you, rare-earth magnets. The major cause of wind turbine failure in the last decade has been the gearboxes breaking down. Because in order to extract power, you have to gear down those giant turbines by quite a bit. And those gears, 300-feet up in the air, tend to break down, they're hard to maintain.

How do you fix it? Make stronger magnets. Put in rare-earth magnets that electromagnetically harvest the energy, instead of gearing it down and doing the same and you don't have mechanical things grinding. What are rare-earth magnets made out of?

AUDIENCE: Rare-earths.

MICHAEL SHORT: Rare-earths. Lanthanides, which happen to be found with actinides, thorium,r whatever actinium exists, radium, uranium, things with similar chemistry. What do you do when you extract the rare-earths that you need from the rare-earth ore? You ditch the remains, which are concentrated sources of these radioactive byproducts. Where do most radioactive-- I'm sorry, where do most rare-earth magnets come from?

AUDIENCE: China.

MICHAEL SHORT: China. How is China's record on environmental practices?

AUDIENCE: Not [INAUDIBLE].

[INAUDIBLE]

[INTERPOSING VOICES]

MICHAEL SHORT: Spotty, at best.

AUDIENCE: Questionable.

MICHAEL SHORT: Yeah. So, again, one of those things where people say, oh, wind power has absolutely no effect on the environment. Check the radioactivity of making windmills.

AUDIENCE: I want you to tell the Sierra.

MICHAEL SHORT: I don't know if the Sierra Club would listen.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: I have heard murmurs or rumors of them coming around to the idea of nuclear power. There's an article that said they switched positions, then there was a counter article, followed a day later, that says, no, that was a rogue actor. They don't reflect the views of the Sierra Club. The problem is with all these neo-envrionmentalists and cell-phones-cause-cancer people and food-irradiation-is-evil people, you'll find them cherry picking data to support the conclusion that they already felt they wanted. And when confronted with overwhelming evidence to the contrary. They don't change their view. And that to me is the best thing about science. If you prove to me that you're wrong, I will say, thank you, not [INAUDIBLE].

AUDIENCE: [LAUGHTER]

MICHAEL SHORT: So, there you go. All right, I'll see you guys on Tuesday.